# Comments Regarding "On Neutrino-Mixing-Generated Lepton Asymmetry and the Primordial Helium-4 Abundance"

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This is a reply to the preprint "On Neutrino-Mixing-Generated Lepton Asymmetry and the Primordial Helium-4 Abundance" by M. V. Chizhov and D. P. Kirilova (hep-ph/9908525), which criticised our recent publication (X. Shi, G. M. Fuller and K. Abazajian *Phys. Rev.* **D 60** 063002 (1999)). Here we point out factual errors in their description of what our paper says. We also show that their criticisms of our work have no merit.



**(1)** The main point of the paper by M. V. Chizhov and D. P. Kirilova [1] (hereafter CK) in regards to Shi, Fuller and Abazajian [2] (hereafter SFA) is that the primordial $^4$He abundance yield in Big Bang Nucleosynthesis (BBN) can be appreciably affected by neutrino mixing (sterile neutrino production) even when the lepton number asymmetry, $L$, is small ($L \ll 0.01$, for example). Of course, this has been known for some time. The change in the $^4$He abundance yield in an extreme case, $L \to 0$, was discussed and calculated as long ago as the early 1980's [3–6]. One of the calculations was in fact done by an author of SFA [6].

On page 2 of the CK paper, it says, "Certainly such consideration (meaning that we only consider the $^4$He abundance change for $L > 0.01$) is valid for the simple case of nucleosynthesis *without oscillations*!" This is in fact a very good (although not 100% accurate) statement regarding the SFA paper. It is obvious that SFA was indeed only concerned with active-sterile neutrino mixings when the relevant mixing angles were sufficiently small that the sterile neutrino production from active-to-sterile neutrino oscillation (other than the MSW resonant active-to-sterile neutrino conversion whose amplitude is much less sensitive to mixing angles) is negligible. This was done for a reason: cases where oscillation effects are large have been considered before, *e.g.*, in the papers cited above. The particular parameter space we chose to examine in SFA was based on the calculation that shows that lepton asymmetry can be generated by mixings as small as $\sin^2 2\theta \sim 10^{-10}$ [7,8]. However, oscillation effects (other than MSW resonant conversion) won't be important until $\sin^2 2\theta \gg 10^{-4}$ for $\delta m^2 \lesssim 1\,\mathrm{eV}^2$ (see figures of Shi '96 [8]). In this parameter space chosen by SFA, neutrinos or anti-neutrinos can be converted (via matter-enhanced MSW) to sterile neutrinos, thus creating a neutrino asymmetry, but the overall neutrino energy density may not be changed significantly. In such a situation, production of asymmetries $L \ll 0.01$ indeed **do not** have an appreciable impact on the primordial $^4$He abundance yield.

This mixing parameter space chosen by us has no overlap with the parameter spaces considered by CK ($\sin^2 2\theta > 0.01$ and $\delta m^2 < 10^{-7}$, from their figure 2, where oscillation effects are important). It is therefore rather ironic that based on an irrelevant comparison of two non-overlapping parameter spaces the authors of CK can claim "The obtained constraints on $\delta m^2$ are by several orders of magnitude more severe than the constraints obtained in SFA."

**(2)** In the footnote of page 2, CK stated that "we are really sorry that..." Here we are happy to report that the authors of CK don't have to be sorry because nowhere in the SFA paper did we claim to be the first to discover this account (of the effects of neutrino spectral distortion and evolution). The effects of neutrino spectral distortion and evolution on $^4$He synthesis have been known since the early studies of BBN, even in the original complete paper on the subject, Wagoner, Fowler and Hoyle 1967 [9]. In SFA we merely apply this account to particular cases of neutrino mixing. We do not know from which page and which paragraph in SFA we can be implicated in a claim of discovery.

**(3)** In regards to the first paragraph of page 8, the authors of CK are welcome to read more carefully Shi (1996) [8], where there is a lengthy discussion on whether the $L$-generation process meets the classic criterion of chaos (see also a recent work of Enqvist *et al.* [10]). They are also welcome to produce any evidence showing what will be the sign of a net lepton number asymmetry $L$ resulting from resonant neutrino transformation. And yes, even though the chaotic feature of the $L$-generation process is not well understood, we will "continue exploiting it fabricating models and constraints." Doesn't any scientific model involve some assumptions that are not well understood? We do not believe that our scientific integrity is in any way compromised when we discuss these models and constraints, because we have always discussed, and will always continue to do so, the underlying assumptions of these models and constraints.

Finally, we should point out that the entire problem of neutrino flavor-transformation in the early universe is a difficult one. Not the least of the difficulties is solving the Boltzmann equation plus the MSW equations for multiple particle species with a spread of energies and occupation numbers. Furthermore, the equations have non-linear feedback terms that may generate chaos in solutions. Many groups have attacked these issues. They

have obtained many interesting and important results. But in our opinion, a satisfactory, general solution has yet to be found. In this sense our understanding of the problem so far is indeed "shallow" and "simplistic." We have no doubt that any future breakthroughs in this problem will offer deeper and more sophisticated understandings of neutrino physics and cosmology.

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[9] R. V. Wagoner, W. A. Fowler, and F. Hoyle, *ApJ* **148**, 3 (1967).

[10] K. Enqvist, K. Kainulainen, A. Sorri, hep-ph/9906452.